LCA Methodology

# Life Cycle Impact Assessment of Pollutants Causing Aquatic Eutrophication

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**Abstract.** In life cycle impact assessment (LCIA), limited attention is generally given to a consistent inclusion of a fate analysis in the derivation of aquatic eutrophication potentials. This paper includes fate and potential effects in the calculation of aquatic eutrophication potentials of $NH_3$ and $NO_x$ emitted to the air, N and P emitted to water, and N and P emitted to soil. These characterisation factors were calculated for the Netherlands, West-Europe and the world, respectively. Implementation in current LCIA practice is further facilitated by calculating normalisation scores for the Netherlands in 1997, West-Europe in 1995 and the world in 1990. Although the results presented may be a step forward, significant improvements are still needed in the assessment of pollutants causing aquatic eutrophication. In particular, the fate factors representing transport of $NO_x$ and $NH_3$ air emissions via soils to the aquatic environment should be improved. In addition, differences in the biological availability of nutrients and differences in the sensitivity of aquatic environments should be included in the calculation of effect factors for aquatic eutrophication.

**Keywords:** Air emissions; aquatic eutrophication; biomass production; fate modelling; impact indicators; LCIA; life cycle impact assessment; nitrogen; phosphorus; soil emissions; water emissions

## Introduction

Up to now, the impact indicator for eutrophication is generally defined as the potential share of eutrophying substances in the biomass formation of aquatic algae (see Heijungs et al. 1992). The actual indicator in use is based on the average carbon:nitrogen:phosphorus (C:N:P) ratio, also called the Redfield ratio, as found by Redfield et al. (1963). A serious drawback of using this impact indicator in LCIA is that it does not represent eutrophying impacts on the terrestrial environment, and that fate, background depositions and ecosystem sensitivity are not included in the current characterisation factors. To improve this situation, Huijbregts et al. (2000) adapted the RAINS model (Alcamo et al. 1990) to calculate terrestrial eutrophication potentials of ammonia ($NH_3$) and nitrogen oxide ($NO_x$) air emissions for Europe and a number of European regions, taking fate, background depositions and effects into account. For aquatic eutrophication, however, there are as yet no similar improvements (see Finnveden and Potting 1999).

A first improvement in the current characterisation factors for aquatic eutrophication may be established by including fate factors in the characterisation of anthropogenic emissions to air and soil (Equation 1).

$$AEP_{s,i,e} = AFF_{s,i,e} \times AEF_s \quad (1)$$

where $AEP_{s,i,e}$ is the characterisation factor for aquatic eutrophication of compound $s$ emitted in region $i$ to compartment $e$ (kg $PO_4^{3-}$-eq·kg$^{-1}$); $AFF_{s,i,e}$ is the fate factor representing the fraction of compound $s$ emitted in region $i$ to compartment $e$ that is transported to the aquatic environment (-); and $AEF_s$ is the effect factor representing potential biomass production of phytoplankton per mass unit of compound $s$ relative to $PO_4^{3-}$ (kg $PO_4^{3-}$-eq·kg$^{-1}$).

Huijbregts and Seppälä (2000) outlined a first step towards fate factors to be used in the calculation of aquatic eutrophication potentials of $NH_3$ and $NO_x$ air emissions for Europe and a number of European regions. The results presented, however, were not directly suitable for obtaining aquatic eutrophication potentials for emissions to air, water and soils. This paper elaborates on the analysis of Huijbregts and Seppälä (2000) by including fate factors in the calculation of Dutch, West-European, and global characterisation factors for air and soil emissions causing aquatic eutrophication. To facilitate the use of these new characterisation factors in life cycle impact assessment (LCIA), normalisation scores for the Netherlands in 1997, West-Europe in 1995 and the world in 1990 are also presented.

## 1 Fate Factors

### 1.1 Air emissions

Fate factors for $NH_3$ and $NO_x$ directly emitted to air in region i ($AFF_{s,i,air}$) reflect two pathways (Huijbregts and Seppälä 2000):

(1) Direct deposition in the aquatic environment ($AFF_{s,i,air\rightarrow aqua}$); and

(2) run-off and leaching to the aquatic environment after deposition on the soil ($AFF_{s,i,air\rightarrow soil\rightarrow aqua}$).

Thus,

$$AFF_{s,i,air} = AFF_{s,i,air \rightarrow aqua} + AFF_{s,i,air \rightarrow soil \rightarrow aqua} \quad (2)$$

where

$$AFF_{s,i,air \rightarrow soil \rightarrow aqua} = \sum_j AFF_{s,i,j,air \rightarrow soil} \times AFF_{s,j,soil \rightarrow aqua} \quad (3)$$

The $AFF_{s,i,j,air \rightarrow soil}$ is the fraction of pollutant s that is transported from region i to the soil compartment of region *j* via dry and wet deposition (-); and the $AFF_{s,j,soil \rightarrow aqua}$ represents the fraction of pollutant s that is transported from the soil in region *j* to the aquatic environment via leaching and run-off (-).

Fate factors for phosphorous compounds directly emitted to air can also be calculated by Equation 2.

### 1.2 Soil emissions

Aquatic fate factors for nitrogen (N) and phosphorus (P) inputs in the soil of region i ($AFF_{s,i,soil}$), due to animal excretion and fertilisation, for instance, may reflect three main pathways:

(1) Run-off and leaching of (in)organic N and P from the soil to the aquatic environment ($AFF_{s,i,soil \rightarrow aqua}$);
(2) deposition on the aquatic environment after volatilisation ($NH_3$) or transport by wind-driven particles (P) from the soil to the air ($AFF_{s,i,soil \rightarrow air \rightarrow aqua}$); and
(3) run-off and leaching to the aquatic environment after volatilisation ($NH_3$) or transport by wind-driven particles (P) from the soil to the air and subsequent deposition on the soil ($AFF_{s,i,soil \rightarrow air \rightarrow soil \rightarrow aqua}$).

Thus, fate factors of N and P emissions to the soil in region *i* transported to the aquatic environment can be calculated by

$$AFF_{s,i,agrisoil} = AFF_{s,i,agrisoil \rightarrow aqua} + AFF_{s,i,agrisoil \rightarrow air \rightarrow aqua} + AFF_{s,i,agrisoil \rightarrow air \rightarrow soil \rightarrow aqua} \quad (4)$$

where

$$AFF_{s,i,soil \rightarrow air \rightarrow aqua} = AFF_{s,i,soil \rightarrow air} \times AFF_{s,i,air \rightarrow aqua} \quad (5)$$

and

$$AFF_{s,i,soil \rightarrow air \rightarrow soil \rightarrow aqua} = AFF_{s,i,soil \rightarrow air} \times \sum_j AFF_{s,i,j,air \rightarrow soil} \times AFF_{s,j,soil \rightarrow aqua} \quad (6)$$

The $AFF_{s,i,soil \rightarrow air}$ represents the fraction of pollutant *s* that is transported from the soil of region i to the air via volatilisation or via transport by wind-driven particles (-).

## 2 Characterisation Factors

Equations 2 and 4 were used to calculate the fate factors for $NH_3$ and $NO_x$ air emissions, and N and P soil emissions, respectively. However, due to the lack of available data, it was not possible to connect the $AFF_{s,i,j,air \rightarrow soil}$ and the $AFF_{s,j,soil \rightarrow aqua}$ for the receiving region *j*. As a preliminary solution, it was decided to calculate the $AFF_{s,i,air \rightarrow soil \rightarrow aqua}$ using fate information only related to agricultural soils. It was assumed that

$$\sum_j AFF_{s,i,j,air \rightarrow soil} \times AFF_{s,j,soil \rightarrow aqua} \approx AFF_{s,i,air \rightarrow soil} \times AFF_{s,i,agrisoil \rightarrow aqua} \quad (7)$$

where

$$AFF_{s,i,air \rightarrow soil} = 1 - AFF_{s,i,air \rightarrow aqua} \quad (8)$$

Table 1 lists the partial fate factors and their average values for the Netherlands, West-Europe and the world. The $AFF_{air \rightarrow aqua}$ for $NO_x$ and $NH_3$ global air emissions were approximated from a long-range transport model for the Northern hemisphere (Galperin et al. 1995, Galperin and Sofiev 1998), taking the ratio of the deposition in the marine environment and the total emission. Depositions in the marine environment of the Northern hemisphere and total emissions were taken directly from Galperin et al. (1995) and Galperin and Sofiev (1998). Deposition in the marine environment of the Southern hemisphere was estimated by multiplying the total deposition exported from the Northern hemisphere (Galperin et al. 1995, Galperin and Sofiev 1998) with the area fraction of the marine environment of the Southern hemisphere (Anonymous 1997). The $AFF_{air \rightarrow aqua}$ for Dutch and West-European $NH_3$ and $NO_x$ emissions were derived from country-specific fate information presented by Huijbregts and Seppälä (2000). Their partial fate factors, however, did not include nitrogen deposition in the marine environment outside Europe. As a first approximation, the correction factors for deposition outside the modelling area used in the calculation of the global $AFF_{NH3,air \rightarrow aqua}$ (0.03) and $AFF_{NOx,air \rightarrow aqua}$ (0.06) were added to the partial fate factors $AFF_{air \rightarrow aqua}$ for $NH_3$ and $NO_x$ emissions in the Netherlands and West Europe. The $AFF_{P,air \rightarrow aqua}$ could not be determined due to a lack of information.

The $AFF_{N,agrisoil \rightarrow air}$ for the Netherlands, Europe and the world was derived from region-specific nitrogen inputs to the agricultural soil via animal excretion and fertilizer use, and corresponding volatilisation data (Van Harmelen et al. 1999, Bouwman et al. 1997). In all cases, the $AFF_{P,agrisoil \rightarrow air}$ was set to zero (Van Harmelen et al. 1999). The Dutch and European $AFF_{agrisoil \rightarrow aqua}$ for N and P were based on the fate information of anthropogenic agricultural soil input for the Netherlands and Europe, respectively (Van Harmelen et al. 1999,

**Table 1:** Values for partial fate factors in the calculation of characterisation factors of emissions causing aquatic eutrophication

| Partial fate factors | Netherlands | Europe | World | Reference |
|---|---|---|---|---|
| $AFF_{NH3,air \rightarrow aqua}$ | 0.29 | 0.19 | 0.17 | a-d |
| $AFF_{NOx,air \rightarrow aqua}$ | 0.34 | 0.27 | 0.32 | a-d |
| $AFF_{N,agrisoil \rightarrow aqua}$ | 0.09 | 0.17 | 0.30 | e-g |
| $AFF_{P,agrisoil \rightarrow aqua}$ | 0.04 | 0.03 | 0.03 | e-g |
| $AFF_{N,agrisoil \rightarrow air}$ | 0.14 | 0.18 | 0.17 | e, h |
| $AFF_{P,agrisoil \rightarrow air}$ | 0 | 0 | 0 | e |

AFF = Aquatic Fate Factor; [a] Galperin et al. (1995); [b] Galperin and Soviev (1998); [c] Anonymous (1997); [d] Huijbregts and Seppälä (2000); [e] Van Harmelen et al. (1999); [f] Beusen et al. (1995); [g] Mosier et al. (1998); [h] Bouwman et al. (1997)

**Table 2:** Fate factors, effect factors and characterisation factors for pollutants causing aquatic eutrophication

| Factors / Emissions | AFF Netherlands | AFF Europe | AFF World | AEF | AEP Netherlands | AEP Europe | AEP World |
|---|---|---|---|---|---|---|---|
| **Air** | | | | | | | |
| $NH_3$ | 0.35 | 0.33 | 0.42 | 0.35 | 0.12 | 0.11 | 0.15 |
| $NO_x$ (as $NO_2$) | 0.40 | 0.39 | 0.52 | 0.13 | 0.05 | 0.05 | 0.07 |
| **Water** | | | | | | | |
| N | 1 | 1 | 1 | 0.42 | 0.42 | 0.42 | 0.42 |
| P | 1 | 1 | 1 | 3.06 | 3.06 | 3.06 | 3.06 |
| **Agricultural soil** | | | | | | | |
| N | 0.14 | 0.23 | 0.37 | 0.42 | 0.06 | 0.10 | 0.16 |
| P | 0.04 | 0.03 | 0.03 | 3.06 | 0.12 | 0.09 | 0.09 |

AFF = Aquatic Fate Factor; AEF = Aquatic Effect Factor; AEP = Aquatic Eutrophication Potential

Beusen et al. 1995). The global $AFF_{agrisoil \rightarrow aqua}$ for N was taken from Mosier et al. (1998), while the global $AFF_{agrisoil \rightarrow aqua}$ for P was set equal to the European value due to the lack of available data. For direct emissions to the aquatic compartment, the fate factors were set to 1. Effect factors, based on the Redfield ratio, were taken from Heijungs et al. (1992).

Fate factors and effect factors were multiplied to obtain aquatic eutrophication potentials for $NH_3$ and $NO_x$ air emissions, N and P soil emissions, and N and P water emissions (Equation 1). Table 2 shows the fate factors, effect factors and characterisation factors of emissions causing aquatic eutrophication.

## 3 Normalisation Scores

To facilitate the use of the aquatic eutrophication potentials (AEPs) in LCIA, normalisation scores for three reference situations were calculated. Normalisation is an optional step in the weighting between impact categories (ISO 1998). The procedure provides the decision maker with a measure of the relative contribution from a product system to the impact categories identified by dividing the potential impact per functional unit by the impact score of a reference situation. Total, yearly emissions for a reference year in a reference region are normally used to calculate normalisation scores. ISO (1998) recommends the use of several reference systems to show the consequence on the outcome of the LCIA phase. Here, normalisation scores were calculated for three reference situations: (1) The Dutch territory in 1997; (2) the European territory in 1995; and (3) the world in 1990. The reference years corresponding to the reference regions were chosen for practical reasons, as they are the most recent years available for all relevant emission data per reference region. For direct N and P emissions to water, however, no (recent) data was available for Europe. In this case, emissions from nine European countries were used to extrapolate to European emission totals. The extrapolation method is based on population numbers, as suggested by Beusen et al. (1995). Population numbers were taken from the World Resources Institute (1996).

In the calculation of normalisation scores, emissions of the Netherlands, Europe and the world were multiplied with the corresponding characterisation factors. Table 3 lists, per reference situation, the normalisation scores for aquatic eutrophication and the relative contribution of the emissions to air, water and agricultural soil to the total scores.

Note that the characterisation factor of N emitted to the agricultural soil as used in the calculation of normalisation scores deviates from the default characterisation factor of N emissions to the agricultural soil, as given in Table 2. To avoid double-counting, the AEP of N emissions to the agricultural soil was set at 0.04-0.13 $PO_4^{2-}$-eq. instead of 0.06-0.16 $PO_4^{2-}$-eq. in the calculation of the normalisation scores for the three reference situations. The reason is that the volatilisation of N from the agricultural soil to the air was already included in the calculation of total $NH_3$ emissions to the air.

**Table 3:** Normalisation scores for aquatic eutrophication in the Netherlands (1997), West-Europe (1995) and the world (1990)

| | Netherlands 1997[a] | Europe 1995[b-k] | World 1990[l-o] |
|---|---|---|---|
| **Air (kg $PO_4^{2-}$-eq., %)** | | | |
| $NH_3$ | $2.32.10^{07}$ (16.5) | $7.27.10^{08}$ (10.2) | $7.66.10^{09}$ (12.9) |
| $NO_x$ (as $NO_2$) | $2.36.10^{07}$ (16.8) | $9.99.10^{08}$ (14.0) | $6.97.10^{09}$ (11.7) |
| **Water (kg $PO_4^{2-}$-eq., %)** | | | |
| N | $1.91.10^{07}$ (13.6) | $1.09.10^{09}$ (15.3) | $9.08.10^{09}$ (15.3) |
| P | $2.23.10^{07}$ (15.9) | $1.30.10^{09}$ (18.2) | $9.70.10^{09}$ (16.3) |
| **Agricultural soil (kg $PO_4^{2-}$-eq., %)** | | | |
| N | $3.62.10^{07}$ (25.7) | $2.57.10^{09}$ (35.9) | $2.28.10^{10}$ (38.3) |
| P | $1.62.10^{07}$ (11.5) | $4.61.10^{08}$ (6.4) | $3.31.10^{09}$ (5.5) |
| **Total (kg $PO_4^{2-}$-eq., %)** | $1.41.10^{08}$ (100) | $7.15.10^{09}$ (100) | $5.95.10^{10}$ (100) |

[a] Van Harmelen et al. (1999); [b] Draaijers et al. (1997); [c] EMEP/MSC-W (1999); [d] EMEP/MSC-W (2000); [e] UBA (1998); [f] Stapleton et al. (2000); [g] World Resources Institute (1996); [h] European Communities (1999); [i] Eurostat (1995); [j] FAO (2000); [k] IPCC (1996); [l] Olivier et al. (1996); [m] Olivier et al. (1998); [n] Mosier et al. (1998); [o] Caraco (1995)

## 4 Discussion

The characterisation factors and normalisation data presented here may be regarded as a first attempt towards the inclusion of a full fate analysis in the LCIA of emissions causing aquatic eutrophication. However, several shortcomings should be solved in future research. First of all, the $AFF_{air \to soil \to aqua}$ of $NO_x$ and $NH_3$ emissions should be calculated by taking into account region-specific deposition and subsequent leaching and run-off instead of using fate factors representative for agricultural soils only. Deposition patterns of $NH_3$ and $NO_x$ air emissions on soils and corresponding data on the transport of N to aquatic systems (Posch et al. 1999, Seitzinger and Kroeze 1998), may substantially improve the current calculation of the (region-specific) $AFF_{air \to soil \to aqua}$ for $NO_x$ and $NH_3$ emissions. These models may also be used to calculate fate factors for direct N and P emissions to other soil types than agricultural soils. Secondly, spatial differentiation in fate factors is only included to a minor extent. The results show that differences between the characterisation factors of the Netherlands, Europe and the world remain within a factor of 1.5 for air emissions and a factor of 3 for agricultural soil emissions. However, fate factors for air and soil emissions may vary substantially from region to region due to differences in geographical location towards the marine environment, and different conditions of climate, plant uptake, land use and soil types (Brentstrup et al. 2000, Grennfelt et al. 1994, Huijbregts and Seppälä 2000). If it is expected that life cycle emissions of eutrophying pollutants are dominantly situated in a few regions, the corresponding *region-specific* fate factors may be needed in LCIA. Region-specific information is currently available for the $AFF_{NH3/NOx,air \to aqua}$ of 44 European regions (Huijbregts and Seppälä 2000). In addition, the region-specific partial fate factors $AFF_{N,soil \to air}$ and $AFF_{N,soil \to aqua}$ may be derived from Brentstrup et al. (2000) or from Posch et al. (1999). It may also be useful to derive *activity-specific* fate factors for N and P emissions to the agricultural soil ($AFF_{s,agrisoil \to aqua}$ and $AFF_{N,agrisoil \to air}$). Particularly in LCAs of agricultural products or processes, activity-specific fate factors may substantially increase the reliability of the results. As shown by various authors (Bouwman et al. 1997, Brentstrup et al. 2000, Cederberg and Mattsson 2000, Matthews 1994), the application of different types of (in)organic fertilizers and farm management may result in different fate factors for emissions to the agricultural soil. Finally, there may be a need for the derivation of the fate factors for direct P emissions to the air. Using only the effect factor in the assessment of P, air emissions will lead to a substantial overestimation of LCIA outcomes for product life cycles with large P emissions to the air.

The current use of effect factors solely based on the Redfield ratio also needs further improvement. The first problem to be tackled is that the total N and P released from various anthropogenic sources may have different capabilities to contribute to aquatic eutrophication, because the chemical forms of nutrients may differ (e.g. Ekholm 1998). In addition, the differences in sensitivity of aquatic ecosystems towards eutrophication are not taken into account in the current calculations, implying that a unit release to the aquatic environment is judged equally important for all aquatic ecosystems. Finally, the concept of 'limiting nutrient' (see Finnveden and Potting 1999) was disregarded. This means that all aquatic ecosystems are currently assumed to be N as well P-limited, leading to a conservative LCIA outcome for aquatic eutrophication. As pointed out by Seppälä (1999), it is possible to include the biological availability of total nutrient loads and the spatial aspects of limiting nutrient in the determination of AEPs for eutrophying emissions in Finland. Further research, however, is needed to extend his analysis to other regions.

## 5 Conclusion

The characterisation factors presented here may be regarded as a significant step forward in the life cycle impact assessment of air and agricultural soil emissions causing aquatic eutrophication. The inclusion of fate factors reduces the importance of N and P emissions to soil towards aquatic eutrophication with a factor of 2.5–7.5 and 25–35, respectively. Fate factors for $NO_x$ and $NH_3$ emissions to air also decrease the aquatic eutrophication potentials of these emissions with a factor of 2–2.5 and 2–3, respectively. Implementation in current LCIA practice is further facilitated by presenting normalisation scores for the Netherlands in 1997, Europe in

1995 and the world in 1990. Nevertheless, important improvements are still needed in the calculation of both fate and effect factors for aquatic eutrophication. Priority should be given to improve the current fate factors for the transport of $NO_x$ and $NH_3$ air emissions via soil to the aquatic environment and to include differences in the biological availability of nutrients and differences in the sensitivity of the aquatic environment in the effect factors for aquatic eutrophication.

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